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AIR TRAJECTORIES AND TURBULENCE STATISTICS FROM WEATHER RADAR USING TETROONS AND RADAR TRANSPONDERS

DONALD H. PACK

U.S. Weather Bureau, Washington, D.C.
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ABSTRACT

An experiment was carried out to determine the feasibility of utilizing weather radar (WSR–57) to obtain air trajectories over tens of miles at altitudes less than 5,000 ft. above the ground.

Five constant volume balloons (tetroons) were released each carrying a lightweight (about 150 gm.) transponder which upon being interrogated by the WSR–57 radar would transmit an identifying signal. All flights were successful and the transponder signals provided positive, unambiguous target identification at ranges and altitudes where the ground clutter made direct reflective positioning impossible.

Although the purpose of the experiment was to test the tracking system, data of particular interest were obtained from the simultaneous release of a pair of tetroons which were tracked for more than 2 hours to beyond 20 mi. Analysis of these two flights provided values of the relative dispersion $\overline{Y^2}$ proportional to t^3 and larger, as well as showing negative separation rates. These flights also provided estimates of viscous dissipation (ϵ) comparable to data by other investigators and illustrate a possible technique for relating the energy transfer to and from large-scale features of the flow. The complexity of air motions on the mesoscale and some of the problems associated with non-stationary non-homogeneous turbulence fields are readily seen from these flights.

1. INTRODUCTION

It has been demonstrated [1, 2, 3] that direct reflective or "skin" tracking of constant volume balloons can provide air trajectories and wind component data to significant distances. However, the radars used in these experiments (SP1M, FPS–16, SCR–584, Mod II, and M–33) were designed for target tracking even though the SP1M had been modified for weather surveillance. An attempt by the staffs of the Weather Bureau Research Station and Weather Bureau Airport Station, Cincinnati to track metallized tetroons with attached passive reflectors using the WSR–57 at Covington, Ky. was unsuccessful. Primarily because of the ground clutter, the tetroon could not be positively identified within about 25 mi. of the radar and the signal return was never very good.

Early in the tetroon program the desirability and probable necessity of using a positive electromagnetic signal to track and identify the floating tetroon was recognized. Mr. Earl Pound of the Cordin Co., Salt Lake City, Utah, developed a preliminary model for use with the APS–3 radar at the Weather Bureau Research Station, Idaho Falls, Idaho. A tethered balloon static test of the transponder principle showed promise, but this particular radar was inadequate for tracking purposes.

The existence of an extensive network of weather radars, specifically the Weather Bureau's WSR–57 system, suggested that a WSR–57-tetroon-transponder system would create an ability to obtain air trajectories in a wide variety of locations and reduce our dependence on scarce and busy tracking radar. The Cordin Co., under Weather Bureau contract, constructed a series of prototype operational transponders for this purpose. To be successful and practical these devices had to meet rather stringent requirements. They had to be sufficiently lightweight to be carried by a small tetroon and to present no significant hazard to aircraft. They had to respond only to radar triggering by the WSR–57's (i.e., only in the 2700–2800 megacycle sec.$^{-1}$ band). The transponders had to transmit identifiable signals over a period of several hours and with a power output sufficient to be detectable over several tens of miles at least. And last but not least, the cost of the operational production models should be sufficiently low to permit quantity usage. The transponders used essentially satisfied these requirements.

2. TRACKING SYSTEM

The tracking system consists of a radar, in this case a WSR–57, a tetroon-borne transponder, and a transponder receiver. Figure 1 is a schematic drawing of the system. The principle of operation is simple. The radar scans in azimuth and elevation until the transmitted radar pulse impinges on the transponder receiver. This received signal triggers the transponder transmitter which emits a nominal 403 mc. sec.$^{-1}$ signal. This transmitted signal is detected by an antenna receiver system and then fed into the video circuit of the radar and displayed on the several (PPI, RHI, and R/A) radar scopes. The transponder position in space is obtained from the directional orientation of the radar antenna (completely analogous to direct target reflection) and the range. The latter is determined by the time delay between the transmitted radar pulse and the returning transponder signal.

Radar.—The radar used was the standard Weather Bureau WSR–57 at the WBAS, Cincinnati, Ohio. This radar has a wavelength of 10 cm. and a nominal power output of 500 kw. Additional details on this equipment have been described by Rockney [4]. The radar can be operated in the search (rotating) mode at a maximum rate of 4 r.p.m., or it can be manually positioned on a target. This latter technique was found the most satisfactory.

Tetroons.—The tetroons used in this experiment are the Mylar balloons constructed by the G. T. Schjeldahl Corp. The tetroons are approximately 60 in. on a side with a nominal volume of 1 m.^{3} when super-pressurized to 10 mb. The balloon weight is approximately 440 gm. The particular tetroons used here were made of clear Mylar. The aluminized film of previous balloons was omitted since tests have shown that the film adds little to the target return from this shape balloon but does add substantially to the cost.

Transponder.—The electronic details and the circuitry of the transponder will not be included here. However, an earlier version has been discussed by Dickson and Pound [5]. Figure 2 is a photograph of the transponder. It can be seen that it consists largely of solid state electronic components to save weight and space. Power was supplied from a 1.5-volt alkaline dry cell battery and a 15-volt B battery (photoflash type). Production models will be cased in a foamed plastic for rigidity and weather protection. The receiver portion of the units was designed for use with the WSR–57 radar and receives radar signals

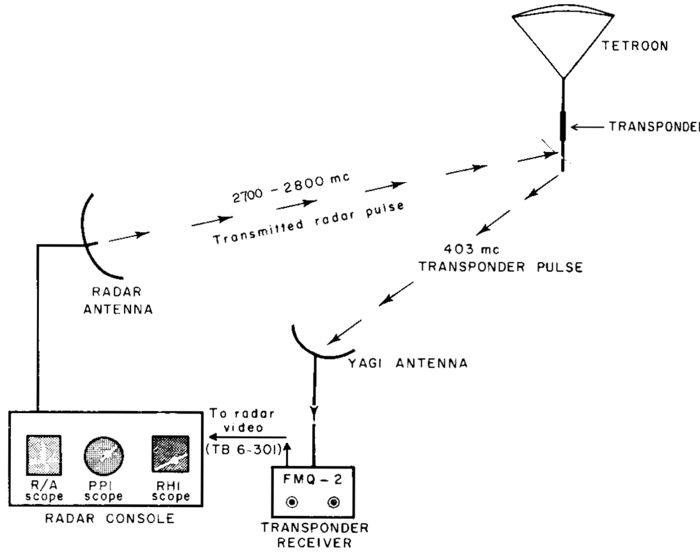

FIGURE 1.—Schematic representation of radar-tetroon-transponder system.

over a nominal 1 mc. sec.$^{-1}$ bandwidth in the range 2700–2800 mc. sec.$^{-1}$ to be compatible with the WSR–57 frequencies. The transmitted signal is a nominal 403 mc. sec.$^{-1}$ with provision for tuning of the individual transponders over a relatively narrow bandwidth. The advantage of this feature will be discussed in a later section.

Receiver.—The transponder signal is detected by an FMQ–2 receiver modified for AM reception and loaned to the project by the Instrumental Engineering Division of the Weather Bureau. A high gain yagi antenna fed the signal to the receiver from a location on the airport terminal building roof immediately above the radar console (to minimize the line loss from long coaxial leads). At first the signal was fed to the radar video circuit through a "mixer", but lack of impedance matching resulted in a large signal loss. After further receiver modifications (by Mr. Pound) it proved possible to feed the signal directly from the FMQ–2 receiver to the radar and in parallel with the regular radar signal. This technique has the major advantage of permitting the use of the radar either for tetroon tracking or for weather observations, simply by reducing the radar video gain to zero for tetroon tracking or alternatively setting the FMQ–2 receiver gain to zero for weather observations. No significant, in fact no detectable change in the normal weather echo signal returns was introduced by this method, a very real advantage when using an operational weather radar.

3. TEST DESCRIPTION

Five tetroon-transponder flights were made using the WSR–57 radar of the WBAS at the Boone County Airport, Covington, Ky., located about 10 mi. southwest of downtown Cincinnati, Ohio. Table 1 lists pertinent release data.

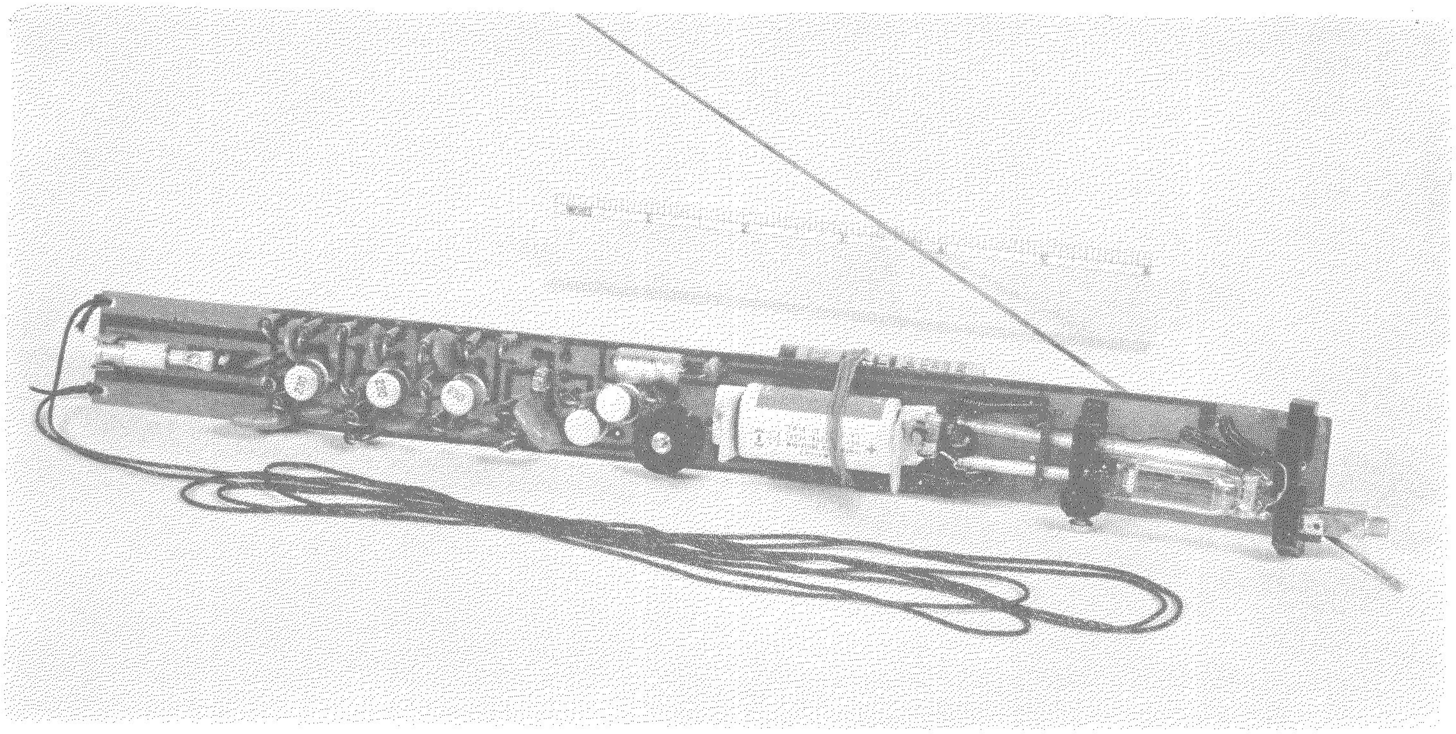

FIGURE 2.—Photograph of radar transponder.

The objectives of these tests were to: test the transponder signal life versus time and distance; test the feasibility of using the WSR–57 for transponder detection and tracking; determine the best WSR–57 tracking procedures; test the ability to acquire the transponder signal when the tetroons were launched at considerable distances from the radar; and determine (approximately) how close to the ground we could detect the transponder when at distances in excess of 10 mi. These objectives were satisfied, and elated by the success of the first two flights, we decided (essentially on the spur of the moment) to attempt to release and track two transponders simultaneously. These flights, numbers 3 and 4, indicated one can indeed track two tetroons alternately with a single radar and provided the most interesting meterological information of the entire series.

TABLE 1.—*Tetroon-transponder flight data*

Flight number	Date May 1962	Release time (GMT)	Release point (from radar) Azimuth (°)	Release point (from radar) distance (n. mi.)	Flight duration (minutes)	Distance tracked (n. mi.)	Maximum radar range (n. mi.)
1	7	2056	266	7.8	82	19.4	11.6
2	8	0115	51	6.5	95	15.4	[1] 12.5
3	8	1806	124	1.7	135	20.4	[2] 21.9
4	8	1806	124	1.7	121	19.2	20.9
5	8	2053	120	<0.5	86	54.4	54.4

[1] Found 2130 GMT, May 8 at Lapel, Ind, 105 mi. northwest of launch site.
[2] Found June 11 "top of Black Mountain, Lynch, Kentucky", 185 mi. southeast of launch site.

In the rolling countryside around the Covington area, and at the distances the tetroons were launched, it was not possible to obtain a positive radar indication of the transponder signal with the transponder held at ground level. In the absence of any method at the launch site for determining if the transponder was actually working, static tests were made by lifting the transponders to between 100 and 400 ft. with a 100-gm. pilot balloon. This action served two purposes. First, a positive signal at the radar insured that the transponder was working and ready for flight. Second, since the launch points were chosen ad hoc there was no positive way of knowing exactly where the release crew was located until the transponder signal was identified.

The procedure followed was to dispatch the launch crew to a location such that the estimated flight path would not cross the airport. This crew located a suitable launch site, advised the tracking crew at the radar of their approximate location (by mobile radio) and suspended the transponder under a tethered balloon. The tracking crew then searched the approximate azimuth until the transponder signal was identified and the FMQ–2 receiver tuned to maximum signal output. The launch crew meanwhile inflated and ballasted a tetroon, and after advice that the transponder was working properly, attached it to the tetroon. Preaddressed postal cards were attached to try to determine tetroon trajectory end points. After a final systems check a 1-minute countdown culminated in the tetroon-transponder release.

Following release, the tracking crew adjusted the radar

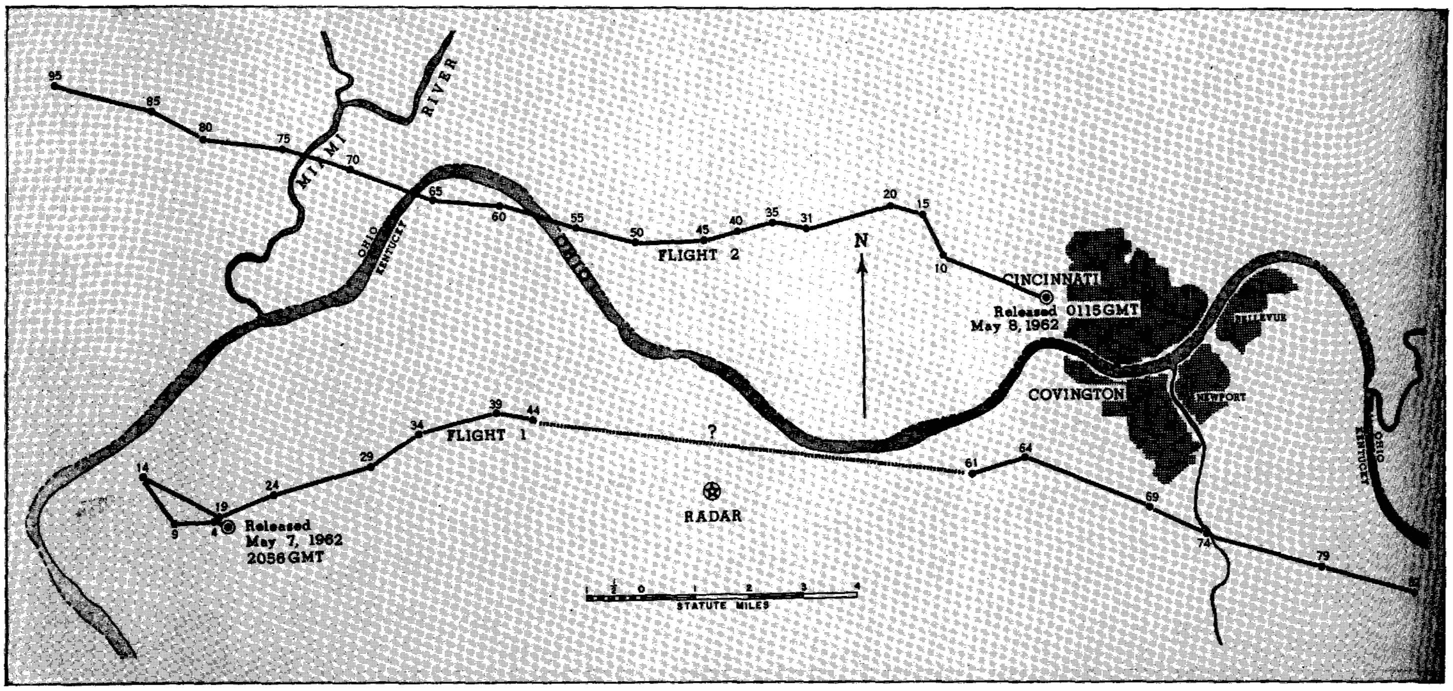

FIGURE 3.—Trajectories of Flights 1 and 2. Numbers at position circles are time (minutes) after release.

azimuth and elevation angles to maintain maximum signal output as measured by the signal height on the R/A scope. From time to time the radar position was optimized and the FMQ–2 receiver tuned to obtain maximum R/A scope output. There was surprisingly little frequency shift in the transponder signal unless the tetroon altitude change caused significant temperature changes. Once the tetroons reached flight altitude any frequency shift was negligible.

These tests show the minimum crew for tetroon flights is probably two men at the radar and two at the launch site. At the radar one man can tune the FMQ–2 receiver and obtain range data from the R/A scope. The second man can operate the radar antenna azimuth and elevation controls and obtain the balloon azimuth and elevation from the PPI and RHI scopes respectively.

It should be mentioned that positive communication between the launch site and the radar console is a must, at least when the tetroons are launched beyond visual range.

It was anticipated that other high-powered and nearby radars would trigger the transponder but we believed this spurious triggering would not interfere with positioning since the lack of signal synchronization would prevent the resulting transponder signal from creating a coherent echo on the WSR–57 scopes. Fortunately the Covington FAA radar provided a verification of this. While the transponder was within about 1½ mi. of this radar it was triggered, but the transponder return was scattered all over the scopes and easily distinguishable from the desired WSR–57 induced signal. Avoidance of this condition is possible by launching from a location not affected by extraneous radars.

The overriding objective of this experiment was the test of the radar transponders and the ability of the radar-transponder-receiver system to give meaningful air trajectories. All other possibilities were subordinate to this test. In spite of this single purpose approach, interesting meteorological data were obtained from Flight 2, and particularly from the dual release of Flights 3 and 4. These latter have been analyzed more extensively and will be discussed in a later section.

Tetroon positions were derived from azimuth, elevation, and range data from the WSR–57 radar. Tetroon heights are the heights above the radar antenna which was 80 ft. above the ground and 950 ft. above mean sea level. A quantitative evaluation of positioning accuracy can not be made with the data at hand. Qualitatively, however, the tetroon range change was detectable to better than 1/100 n. mi. on the R/A scope, and azimuth to better than 1/10 degree (beyond 1 to 2 mi.). Heights were less certain although *changes* in height of 200 to 400 ft. appear to be readily detectable.

The trajectories obtained from Flights 1 and 2 are shown in figure 3. The times after launch are shown along the flight path.

Flight 1.—This initial flight climbed through a surface layer of easterly winds into a westerly wind flow aloft. Since this flight was made with the video mixer in the circuit, the signal return was less satisfactory than on later flights when this feature was eliminated.

Flight 2.—This tetroon was launched from the Gest

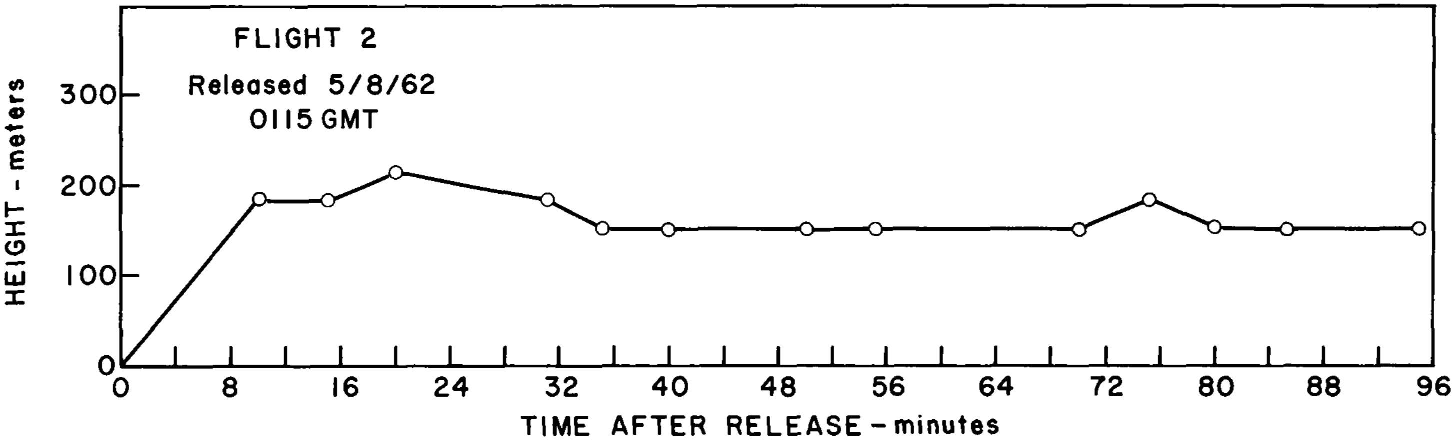

Figure 4.—Height profile of Flight 2.

Street Observatory of the WBRS, Cincinnati in the Mill Creek Valley of the Cincinnati industrial area. It was necessary to lift the transponder to 300 to 400 ft. above the ground before a positive signal was received by the radar. However, the flight signal was picked up within a few minutes of tetroon release and in spite of the proximity to the terrain the signal remained strong and easily tracked for almost the entire flight. This flight was released after sunset and after the lower layer of the air had begun to stabilize. The vertical motion of the balloon was very slight. The flight profile is shown in figure 4.

This flight determined to our satisfaction that tetroons *with transponders* can be followed for significant distances even when very close to the ground. Without transponders this is impossible. Returning the radar video gain to normal levels resulted in ground return of sufficient strength to completely mask even the transponder signal, thus ruling out "skin" tracking with this radar at such low altitudes. Examination of a topographic map of the area traversed by the balloon indicates that although it averaged 400 to 600 ft. above the radar elevation it must often have been within 100 ft. of the ground over which it flew. This balloon was found 20 hr. later in a tree near Lapel, Ind., 105 mi. northwest of the launch site.

Flight 3 and 4.—See section 4 following.

Flight 5.—This tetroon was launched in a partially deflated state without ballast to obtain a relatively high altitude flight, the major purpose of which was to test the transponder signal strength vs. range. The launch point was the roof of the airport terminal building. After losing the signal for several minutes, a very strong signal was acquired and the flight tracked for 86 min. to 54 n. mi. It appears that about 40 min. was required for the tetroon to reach its flight altitude.

To summarize the transponder and radar tracking results of these flights, we believe that the transponders have, even for the first generation prototypes, sufficient signal strength and lifetime to permit the determination of air trajectories over meaningful distances. We strongly suspect that the signal fading which terminated most of the low-level flights is as much due to terrain attenuation of the radar signal (elevation angles were very low) as to attenuation of the transponder signal. This latter can be improved and we expect that the range limitation for very low flights may eventually be a function of radar power output.

The WSR–57 radar was demonstrated to be satisfactory for tracking the transponders. Since the radar was never designed for this purpose, it is not strictly fair to complain of its shortcomings, but they are listed here for information. The readout facilities for range, azimuth, and height are too coarse. Height determination is especially inadequate, as the RHI scope scale is too compressed and the digital elevation angle readout on this instrument had too much lag and backlash to be of assistance. Range determination and readout is adequate beyond about 1 or 2 mi. The transponder signal return is optimized by closely watching the height (proportional to signal strength) of the return on the R/A scope. A sensitive signal strength meter (db. meter) would make this easier. Use of this radar for measuring the high frequency turbulent motions of the tetroons, as has been done with the M–33 and especially with the FPS–16 radars, is probably not justified. All in all, however, we believe that this radar is quite satisfactory for trajectory determination, and within limits for the determination of three-dimensional wind motions.

4. SIMULTANEOUS RELEASE OF TWO TETROONS (Flights 3 and 4)

The primary reason for releasing two tetroons simultaneously was an attempt at one of the more interesting experiments in atmospheric diffusion, namely, the measurement of the spread of a cloud or "puff" of particles. Brier [6] in a classic paper has shown how a series of measurements of the spreading of two particles can be extended to n number of particles. Provided that the turbulence field is stationary and homogeneous it is

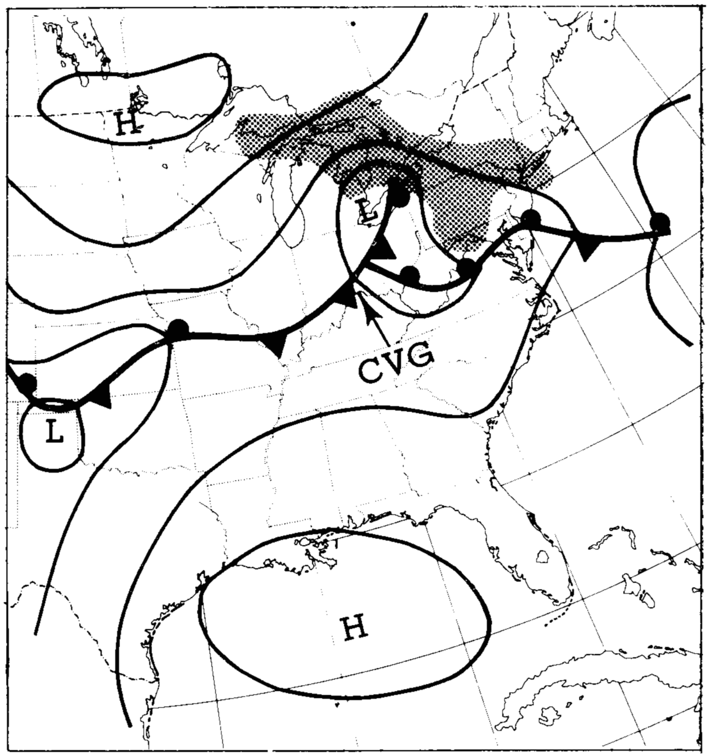

FIGURE 5.—Synoptic situation during Flights 3 and 4 (from *Daily Weather Map* series). Location of Cincinnati airport station is marked by call letters CVG.

possible to use a long time series of two-particle position data to infer ensemble statistics for shorter periods. Although we were reasonably certain that the turbulence field would not meet these requirements, we were sufficiently encouraged by results of previous flights to make at least a single "two-particle" release.

The weather was excellent for the test. Visibility was good and the sky cover consisted of scattered cumuli with a broken to overcast cirrus layer. The lower layer of the atmosphere appeared to be moderately unstable and well mixed. Figure 5 shows the 1800 GMT weather map analysis (taken from the *Daily Weather Map* series) for May 8. The tetroons were very carefully inflated to the same super-pressure and ballasted to as nearly identical free lift as possible. Inflation was in the enclosed grease rack area of a service station run by a most accommodating (and curious) operator. For these flights the transponders were tuned to slightly different frequencies (401 and 406 mc. sec.$^{-1}$). After both transponders were determined to be working, the two tetroons were launched (almost) simultaneously. Actually one tetroon caught momentarily on a cuff button and was released about 3 sec. (approximately 15 m.) behind the first.

Tracking was begun immediately by tuning the FMQ-2 receiver to a transponder frequency and the radar operators then scanned rapidly over the approximate azimuth and elevation until a good position fix was obtained. The receiver was then rapidly re-tuned to the alternate transponder frequency and the process repeated. This "search and fix" procedure never permitted the simul-

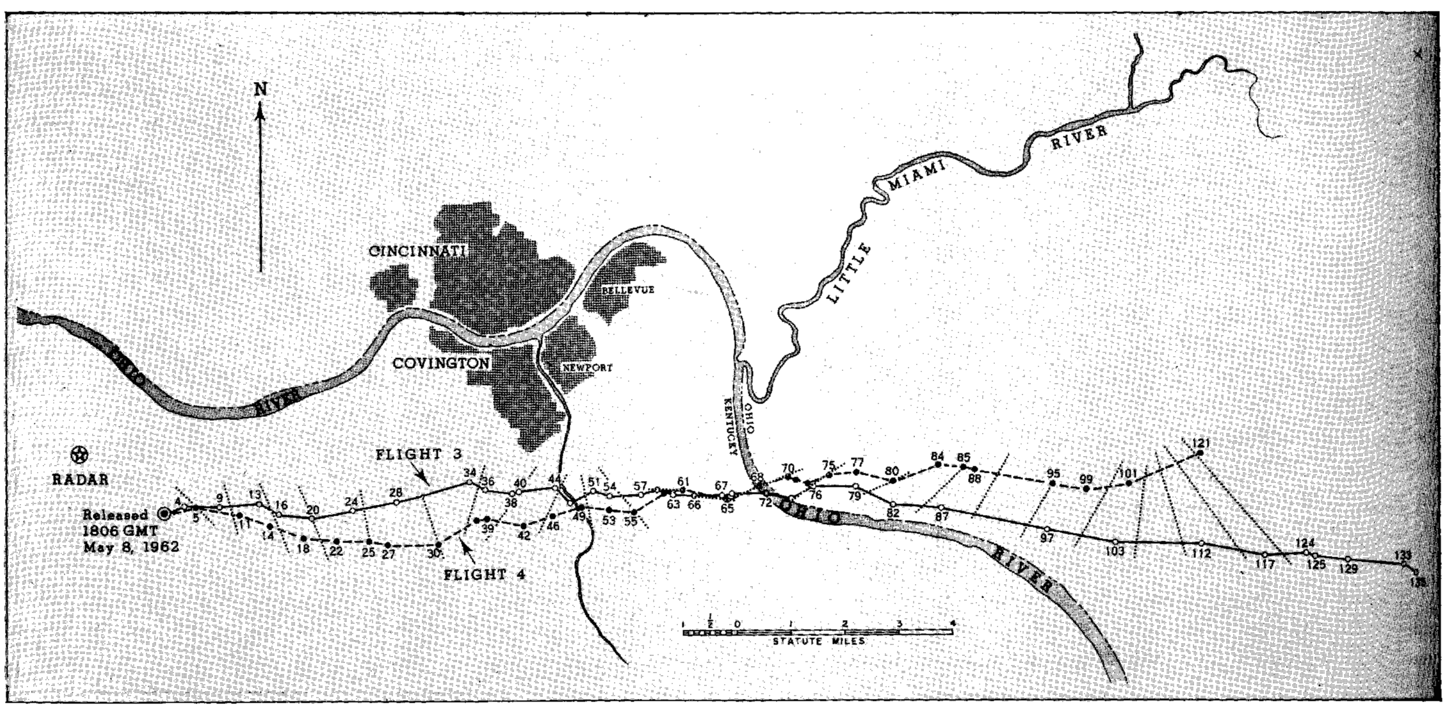

FIGURE 6.—Trajectories of Flights 3 and 4. Numbers at position circles are minutes after release. The light lines across the trajectories are isochrones at 5-min. intervals.

taneous positioning of the two tetroons, but for about the first 90 min. of the flight only 1 or 2 min. separated the tetroon fixes. The tetroon trajectories, and the times they were positioned, are shown in figure 6. Also included in this figure are isochrones at 5-min. intervals. It is immediately evident that one tetroon was alternately ahead of, then behind, the other. Three such reversals of position occurred. Note also that the two trajectories crossed three times. It is also apparent from this illustration that it took longer (became increasingly difficult) to switch from tetroon to tetroon near the end of the flight. Contrary to our expectation we found that the relatively broad radar beam did not trigger the transponder unless the antenna was very carefully directed toward the balloon. Beyond 1 or 2 mi. a slight change in antenna position could be observed as a definite decrease in signal strength. This sensitivity is gratifying in terms of the accuracy of positioning but it adds to the burden of manual tracking and essentially rules out the use of the radar in the search (rotating) mode.

The three-dimensional positions of these tetroons give data that can be examined in at least three ways: first, using the joint statistics to look at the relative positions and separation rates; second, comparing the statistics of each flight to see what differences result even from simultaneous releases; third, to determine what information on meteorological parameters can be derived and if there are recognizable patterns.

a. JOINT STATISTICS

Since the tetroons could not be positioned simultaneously, and since the intervals between positions were irregular, it was necessary to derive sets of continuous statistics. This was accomplished by determining the actual x, y, and z tetroon positions and by linear interpolation at 2-min. intervals deriving a time series for these variables. Since the average trajectories were almost exactly east-west a rectilinear coordinate system oriented east-west (x), north-south (y), and vertically (z) was used. Thus division of the change Δx by the time interval Δt ($=2$ min.) gave the longitudinal values u; similarly $\Delta y/\Delta t$ gave v, and $\Delta z/\Delta t$ gave w.

Since this section was opened with remarks concerning the use of this technique in diffusion experiments, this aspect will be discussed first. Figure 7 shows the tetroon separation distances versus time. The four curves show the total three-dimensional separation R and the individual components of this total, ΔX, ΔY, ΔZ. The most

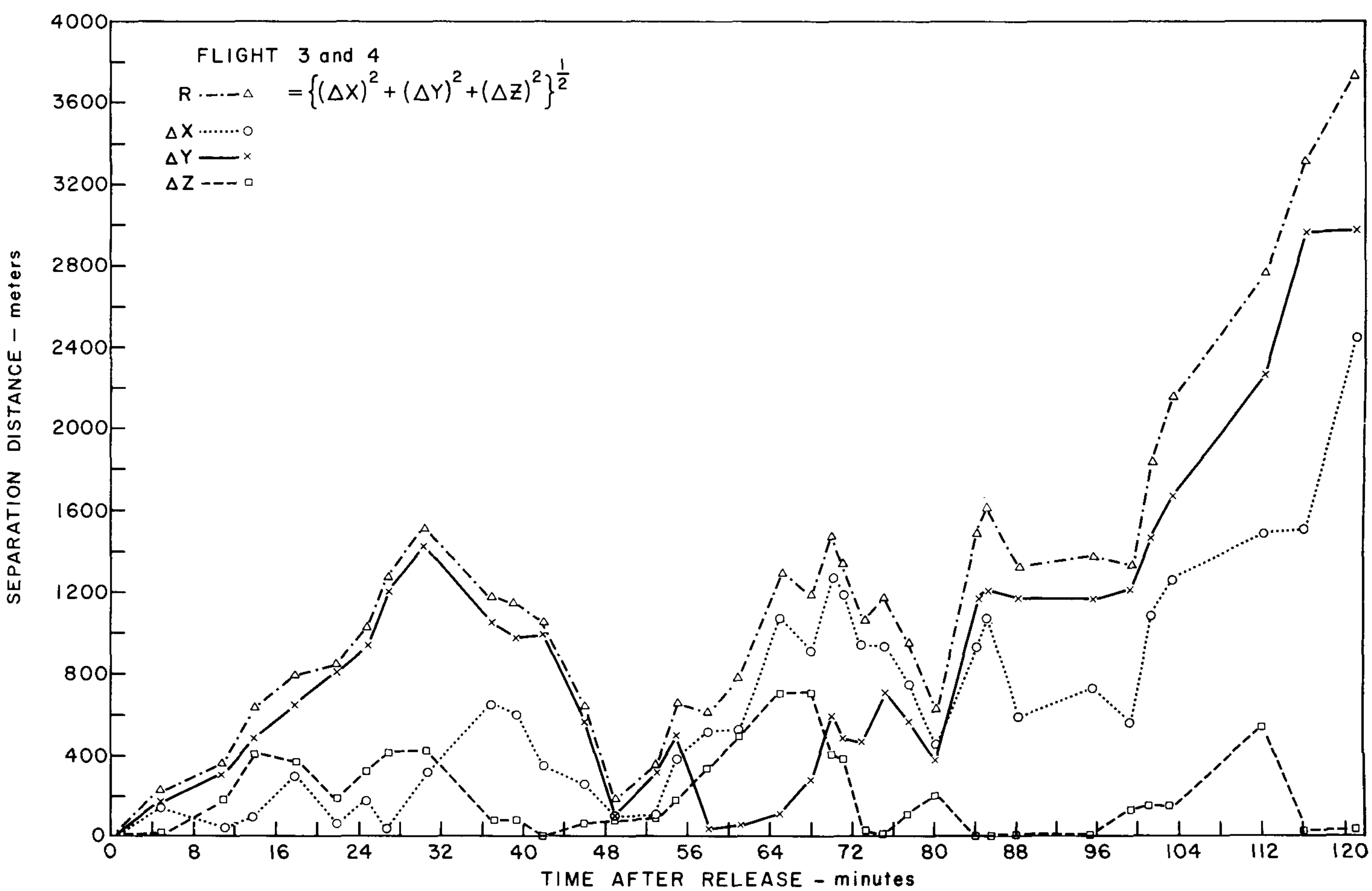

FIGURE 7.—Tetroon separation versus time after release.

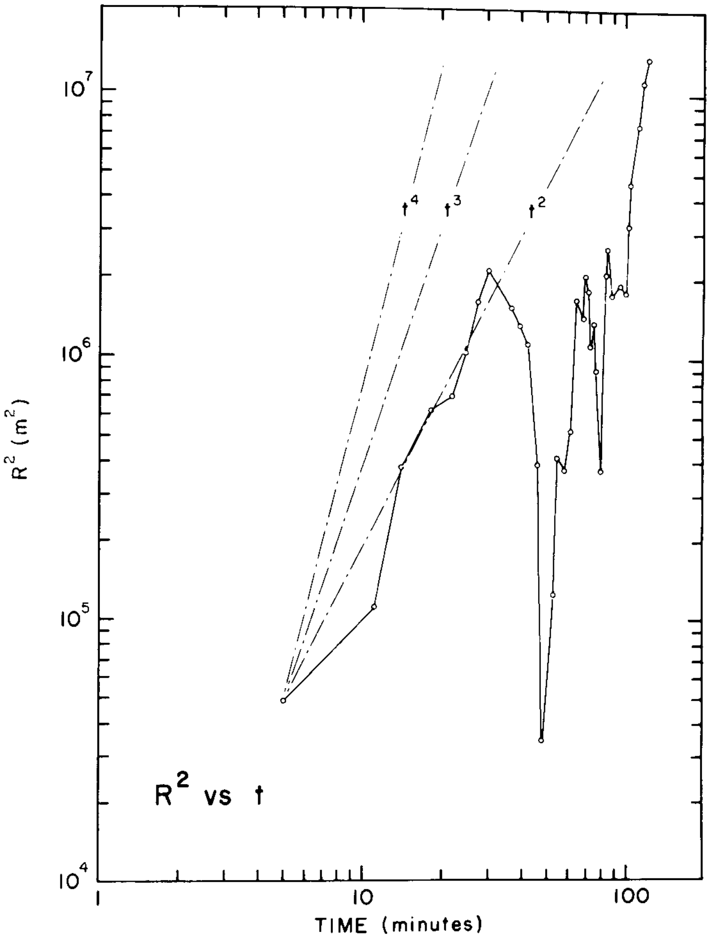

FIGURE 8.—Square of the total vector separation R^2 versus time. Shown for comparison are separation rate $\propto$ t^2, t^3, and t^4.

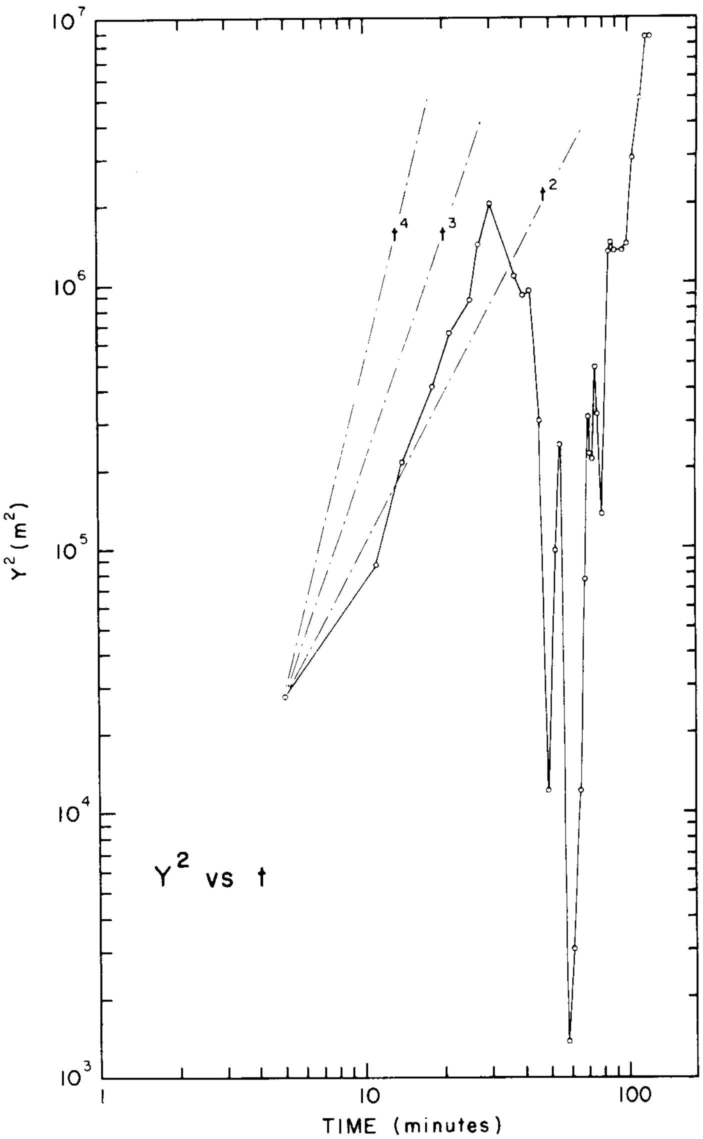

FIGURE 9.—Square of the lateral Y^2 separation versus time. Shown for comparison are separation rates $\propto$ t^2, t^3, and t^4.

obvious and perhaps most interesting aspect is that the balloons did not continually move farther apart. We see that near 32 min., 69 min., and 84 min. the tetroons actually began to move closer together. This is particularly striking between 32 and 49 min. where in 17 min. the tetroons after having separated by almost a mile closed to within about 200 m. total separation and less than 100 m. separation in each of the component directions. From this figure we also see that while, by and large, lateral separation was the dominant factor there was a period (56 to 80 min.) when the x or z separation, or both, were larger. It thus is immediately apparent why repetition of this experiment over many trials (an ensemble) would be required to obtain a reliable measure of the mean atmospheric dispersion rate.

With this in mind, and disclaiming any generality, it is still of interest to examine the separation rates since to the author's knowledge these are the only detailed data on the separation of two "particles" over a 20-mi. trajectory. It should be noted that this type of experiment is examining "relative dispersion" for which Batchelor [7] indicated separation rates in a restricted range proportional to t^3. This prediction was verified by Gifford [8] through the examination of smoke puff data. Later the spreading becomes as t^2 and after a sufficiently long time the rate dispersion should decrease further, and eventually be proportional to t^1. It has long been the goal of tracer experiments to determine the spatial or temporal scale at which such transitions take place. As far as this single test is concerned, the goal is still to be reached. Figures 8 and 9 show the (squared) total separation and the (squared) lateral separation as a function of time after tetroon release. Also shown for convenience are separation rates proportional to various powers of the time. In figure 8 two things stand out clearly: first, that the separation over the early portions of the flights, and the total separation over 120 min. is close to a t^2 regime; second, during the latter portion of the flight the separa-

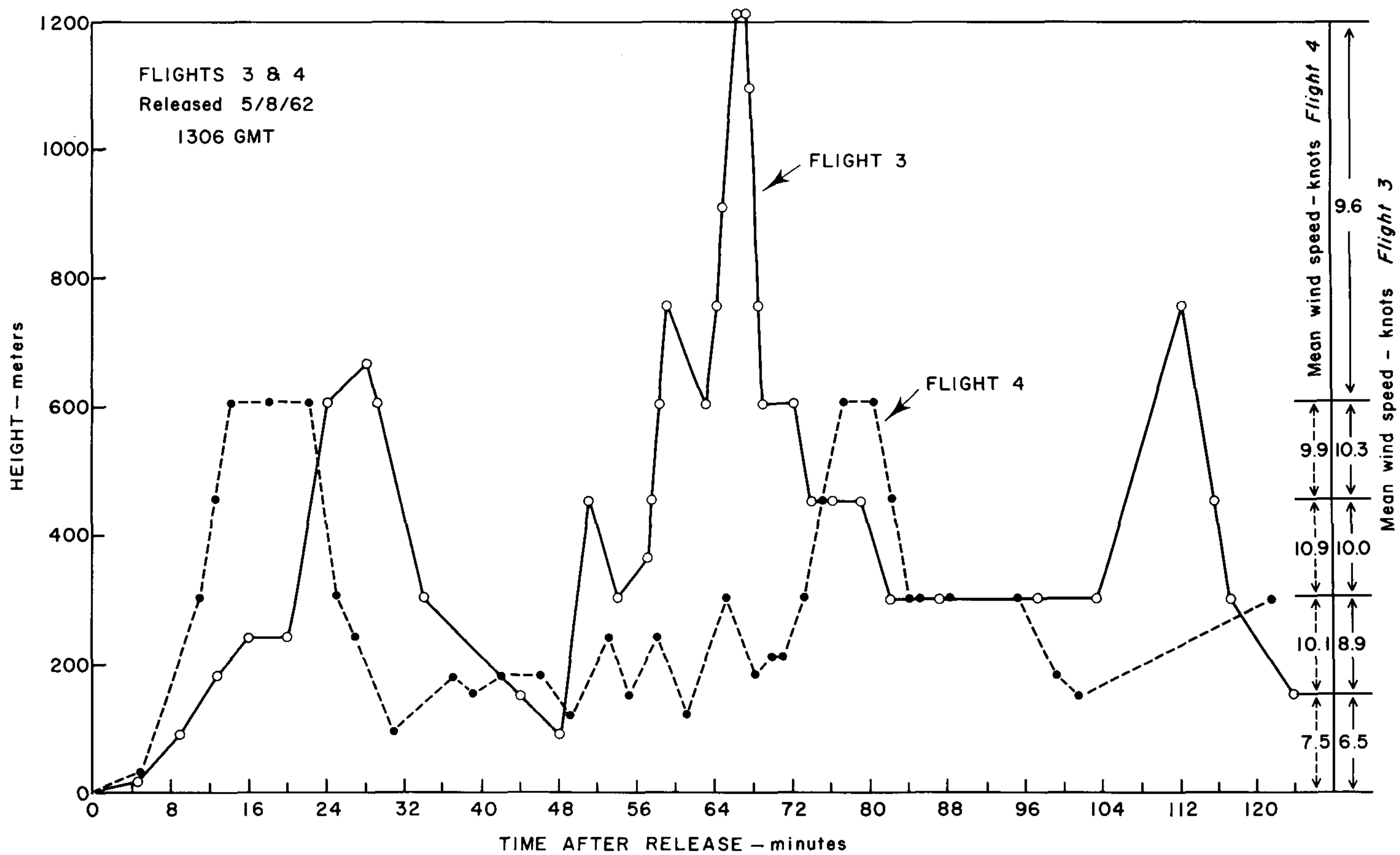

FIGURE 10.—Height profiles, Flights 3 and 4; derived wind speed profile (right ordinate).

tion is more nearly proportional to t^3 or even higher powers of time. In figure 9, the lateral separation seems to be invariably proportional to higher powers of the time, nearly as t^3 for the early portion and t^4 or more during the later stages. Of course, up till now nothing has been said about negative separation rates, nor is it possible to say more than that the event was observed and that only serial releases of two tetroons can provide the data needed for a complete experiment.

b. COMPARATIVE STATISTICS

We turn now to comparisons of the data from the individual flights. Figure 10 shows the unsmoothed height profiles for the two flights and derived wind speed profile data (along the right ordinate). These latter data were obtained by determining, for the indicated height intervals, the time and distance traveled by each tetroon while in each layer. From this information wind speeds were computed. The most significant difference in the two flights is obviously the much larger vertical amplitude of the middle oscillation of Flight 3. There is also a phase difference in the timing of major vertical motions. In order to examine this further, autocorrelations of the individual components were calculated and these are shown in figures 11, 12, and 13. (Spectral analyses might have facilitated comparisons, but for a single experiment and with the knowledge that positioning accuracy deteriorated with distance such refinement is hardly justified.) In fact, the autocorrelations serve very nicely to show major differences in the u and v components. In the longitudinal component Flight 4 shows a marked cyclic character with the period of the oscillations 12 to 41 min. In contrast, Flight 3 is much more irregular with what periodicity there is varying from 16 to 38 min. although the average period is near 25 min., almost twice that of its companion. No obvious explanation comes to mind nor is there any obvious relation to the v or w components. If we now look at the v autocorrelations in figure 12 we find that Flight 3 here shows more frequent oscillations and the average period of 25 min. is the same as the u period for the same flight. In Flight 4 the v period seems confined primarily to a long (78-min.) period. Before leaving this component, note that for about the first 50 min. the autocorrelations are almost exactly 180° out of phase, and in fact the v component stays out of phase for most of the flight.

Before proceeding to the vertical component data we must also recognize the large differences in the absolute

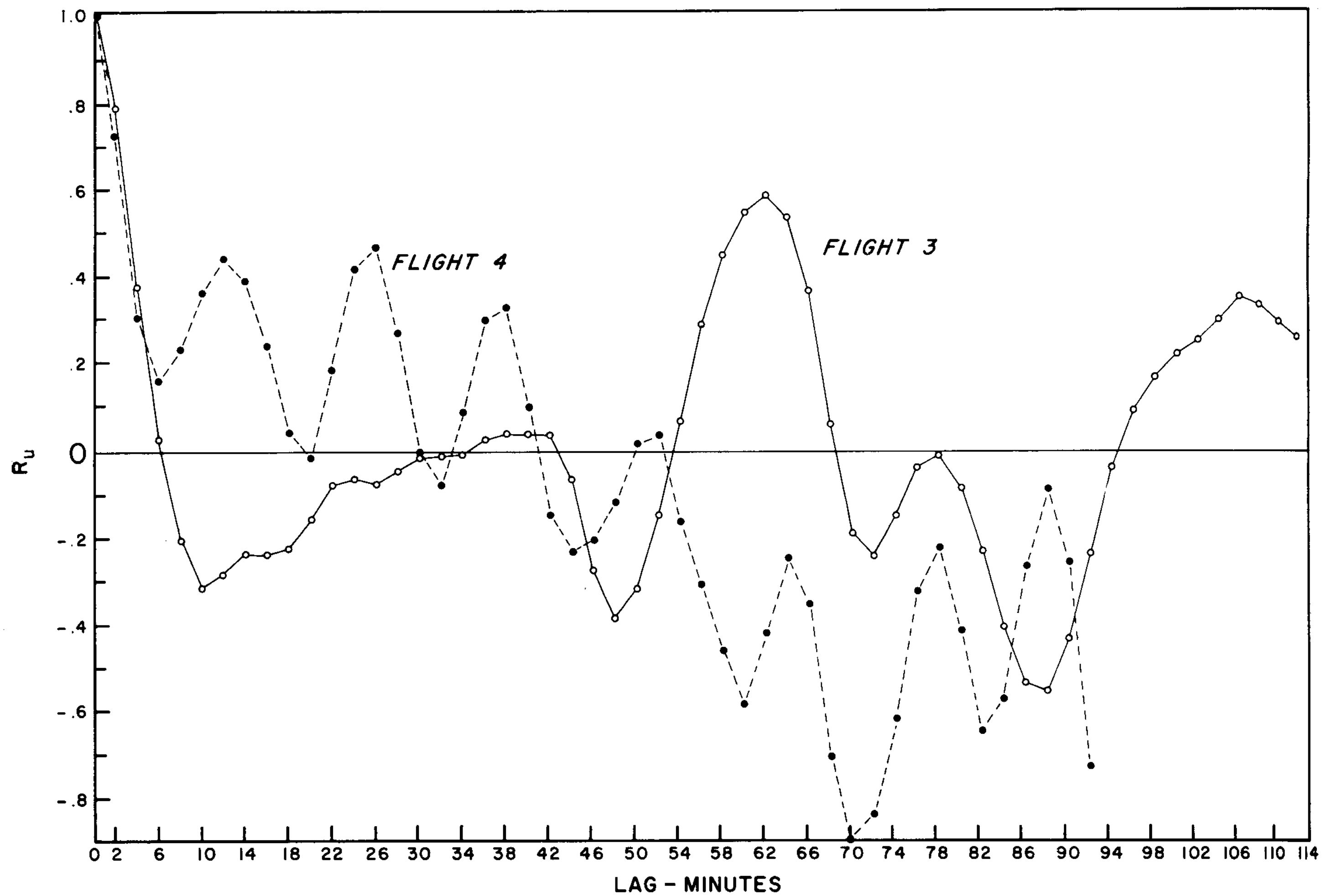

Figure 11.—u-component autocorrelation.

values of these statistics. Since the tetroons were from identical stock, launched in as nearly identical condition as possible, and subject to the same positioning error possibilities, it must be concluded that the observed differences are due to real atmospheric differences.

Turning now to the vertical wind component we can see that these autocorrelations are much more nearly alike. If we lean most heavily on the early portion of the flights, when the positioning was more frequent and more accurate and for which the mathematics of this statistic are better behaved, the two flights are, qualitatively, almost identical. Both flights show major and repetitious periods which average 41 min. in length for Flight 3 and 43 min. for Flight 4. The phase relationship is also very similar and stays about the same with Flight 3 about 90° (10 min.) ahead even though Flight 3 overtook and passed its companion.

It has been shown that the tetroons respond closely to the theoretical periodicities expected of air parcels. Since we infer from the existing weather the lapse rate was very near the dry adiabatic, these 40+ min. periods are of the appropriate length. It is also of interest that similar periods were observed under unstable conditions at Las Vegas [2] although the vertical turbulence intensity was greater there by a factor of 3 or more. Thus the period of the vertical turbulent fluctuations appears unaffected by vertical turbulence intensity.

From the above discussion we can conclude that the component motions sensed by the pair of tetroons showed the most coherent organization in the vertical, and least in the longitudinal direction.

A final note on the differences in the statistics of these two flights is offered. Gifford [9] shows the running mean statistic of the wind components can be used to obtain mean square dispersion values vital to atmospheric dispersion study. For the lateral spreading this becomes

$$\overline{Y^2}(T)=\overline{v'^2}T^2$$

where $\overline{v'^2}$(m.^{2} sec.$^{-2}$) is the running mean variance obtained over the appropriate time interval, and T=dispersion time (sec.).

The $\overline{Y^2}$ values were computed for Flights 3 and 4 and

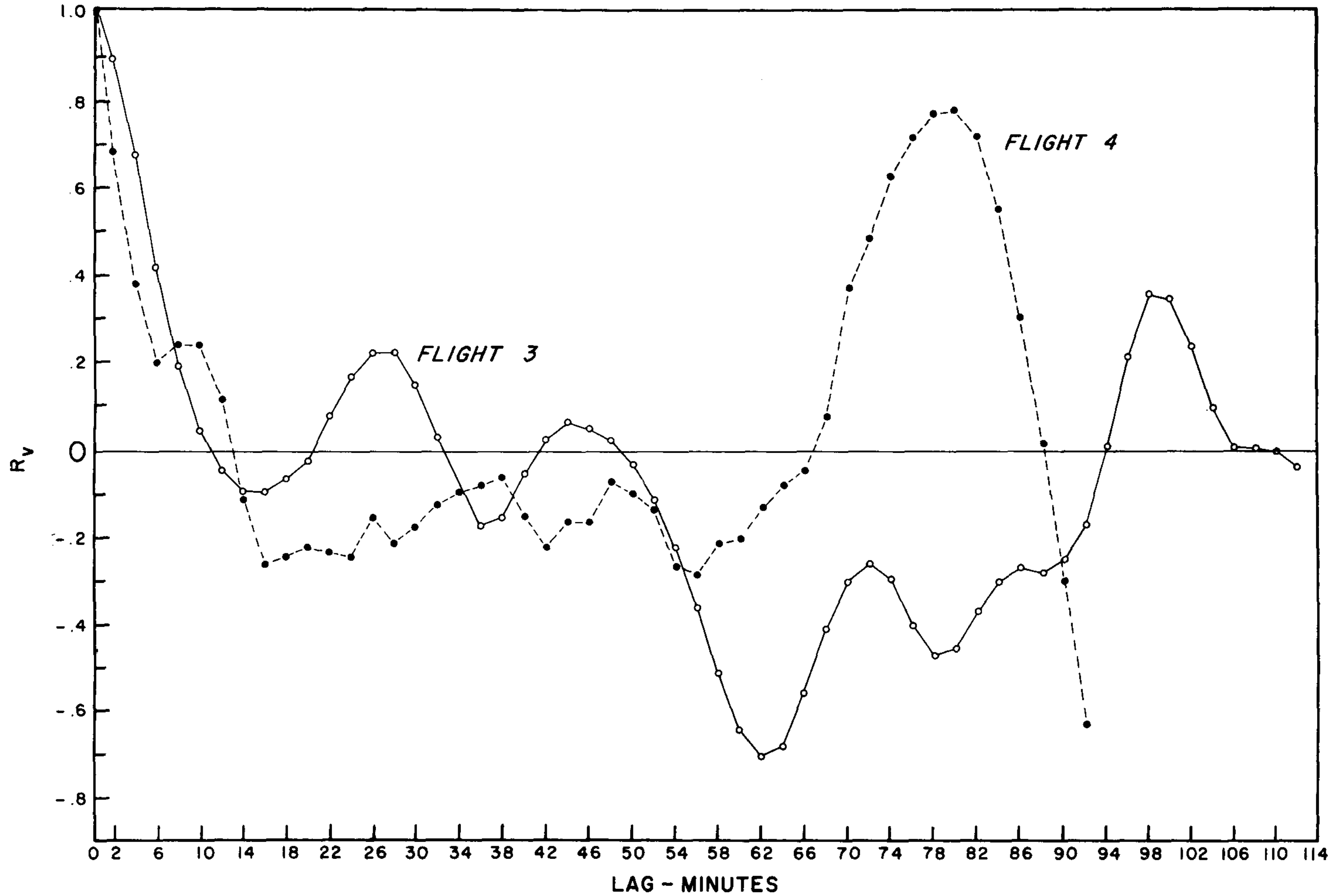

Figure 12.—v-component autocorrelation.

are shown in figure 14. Out to about 20 min. the mean square dispersion is less for Flight 4 by a factor of ~ 2. However after 20 min. the roles are interchanged and Flight 4 gives larger values of this statistic again by a factor of about 2. These differences are not unduly large but the result does reinforce the suggestion of Angell [10] on the development of a climatology from a number of flights rather than utilization of a single flight for estimates of diffusion.

c. METEOROLOGICAL PARAMETERS

It has been previously mentioned (section 4.b.) how wind speed profile data were computed. Thus we have a measure of $\delta u/\delta z$. It is of course time and space dependent but then so are pilot balloon and rawin data which have been used for the same purpose and our statistics are better than a single winds-aloft measurement.

Since we have u and w, we can obtain the turbulent fluctuations u' and w'. From these one can compute the shearing stress τ [11],

$$\tau = -\rho \overline{u'w'}$$

where ρ=air density and u', w'=longitudinal and vertical turbulent wind fluctuations.

An attempt was made to do this for 100-m. height intervals using derived values of density from the NACA Standard Atmosphere [12]. (The nearest radiosonde in the warm air mass within which Flights 3 and 4 took place was Nashville, Tenn., too far to be considered representative.) One would have liked to determine the variation of shearing stress with height; however, this attempt was unsuccessful because of insufficient data within all except the 450–550 and 550–650-m. layers. Nevertheless, the data used in this calculation are shown in table 2. The lack of sufficient data could be remedied by making serial releases during relatively steady state macro-meteorological conditions.

The data of table 2 and the information on $\delta u/\delta z$ can be used to calculate another parameter of interest, namely the eddy energy dissipation (ϵ). Recent papers by Lettau [13] and by Ball [14] have collected data on eddy energy dissipation rate versus height determined by a variety of methods. With our data we calculate ϵ by

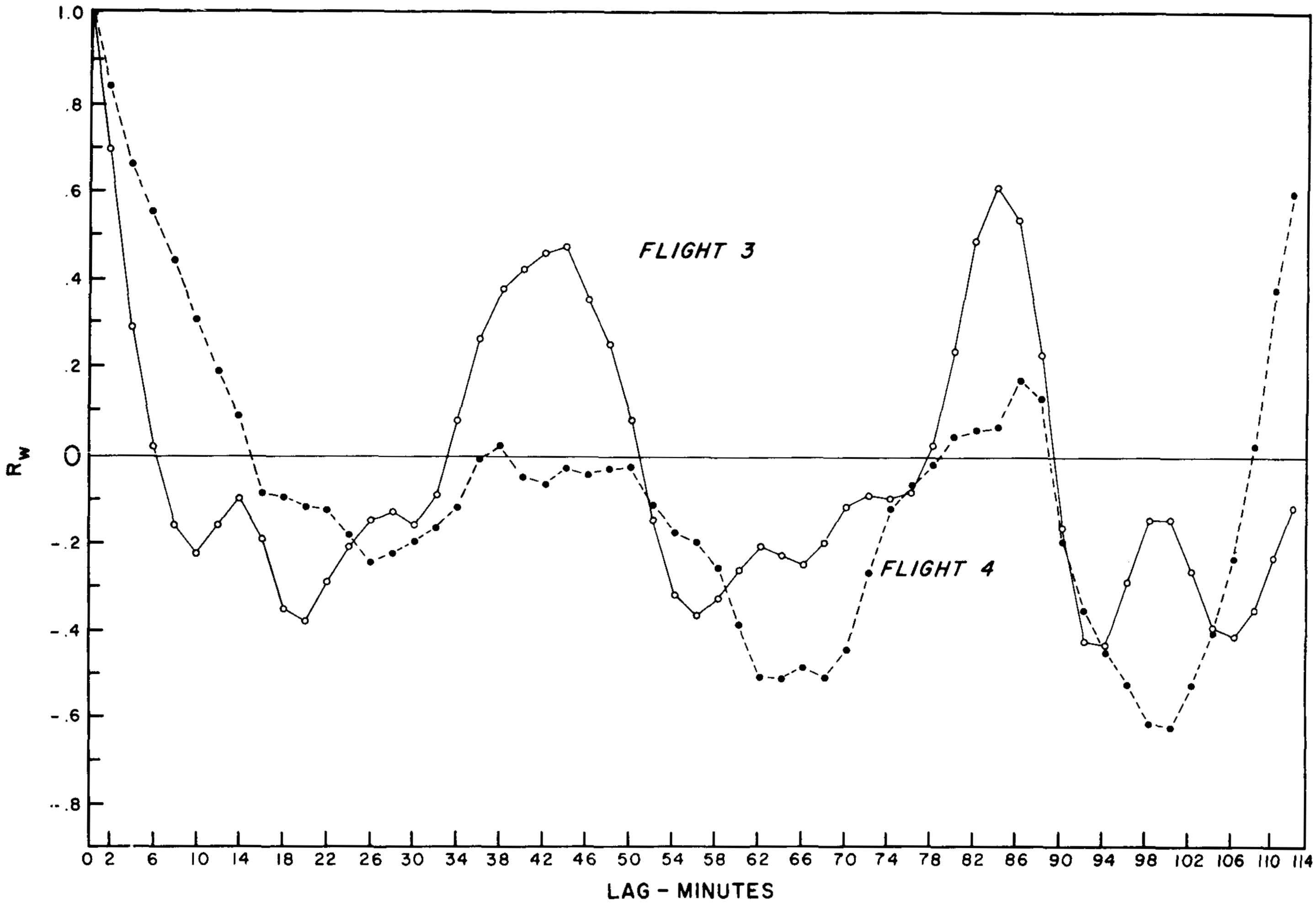

FIGURE 13.—w-component autocorrelation.

$$\epsilon = \frac{\tau}{\rho} \frac{\delta u}{\delta z}$$

or

$$\epsilon = \overline{u'w'} \frac{\delta u}{\delta z}$$

where u' and w' are the longitudinal and vertical wind fluctuations and $\delta u/\delta z$ is the tetroon-derived speed shear. While this is strictly valid only for neutral (dry adiabatic lapse rate) stability, at the time and height of these data the lapse rate must have been very close to neutral. A further restriction is that ϵ should be equal to the rate of production through shearing stresses (i.e., steady state).

If we confine ourselves to the layer centered at 600 m. where we have a comparable number of observations (see table 2) and use the average shear (0.0031 sec.$^{-1}$) from a combination of Flights 3 and 4 ϵ is computed to be 3.78 cm.^{2} sec.$^{-3}$ for Flight 3 and 5.86 cm.^{2} sec.$^{-3}$ for Flight 4. If we refer these values to Ball's [14] figure 3 or to Lettau's [13] figure 1 it is seen that the values, while slightly larger, are consistent with the results of other investigators. Use of the larger $\overline{u'w'}$ values from Flight 3 at 700, 800, and 900 m. would vary (increase) ϵ by only a factor of about 2 since $\delta u/\delta z$ is reduced by nearly ½ through this thicker layer. Obviously the agreement with other data must be viewed with considerable caution for such a small sample. However, the advantage of this technique is considerable since it is quite direct, does not require visual observations (as does the puff diffusion technique), is not severely height limited (as are tower techniques), and finally, provides a spatial average that could be very useful in numerical prediction on the mesoscale. Use of this method for obtaining the viscous dissipation at intermediate heights over a variety of weather situations should be exploited to better understand its seemingly wide variation.

TABLE 2.—*Shearing stress* (τ) *versus height*

Height (m.) 100-m. layer centered at—	Flight 3			Flight 4		
	$\overline{u'w'}$ (cm.^{2} sec.$^{-2}$)	τ (dynes cm.$^{-2}$)	No. of obs.	$\overline{u'w'}$ (cm.^{2} sec.$^{-2}$)	τ (dynes cm.$^{-2}$)	No. of obs.
400	40	−0.06	5	−1970	2.26	6
500	50	−0.06	7	−610	0.71	25
600	−1220	1.37	19	−1890	2.12	14
700	−5250	5.84	5			5
800	−4270	4.70	5			5
900	−5620	6.13	8	−1440	1.57	7

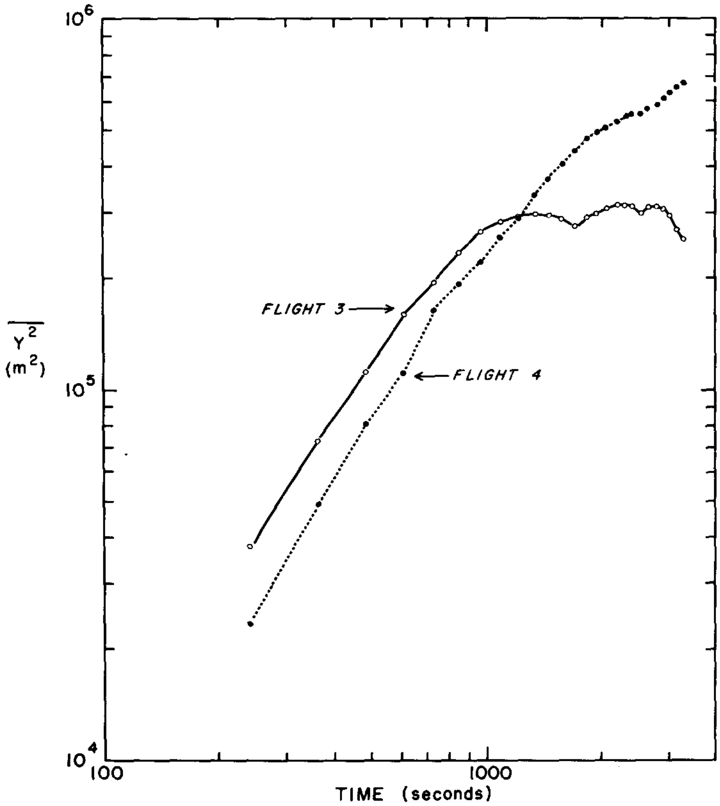

FIGURE 14.—Mean square separation $\overline{Y}^2$ versus time.

It is also possible to derive statistics giving a measure of the amount of stirring or "turbulence intensity" in the atmosphere. This has been done with previous tetroon flights and similar data are included here (table 3) for comparison. The values for the two flights differ, but not radically. The pertinent statistic for comparison with other tetroon flights is probably vertical turbulence intensity. The average value for these runs (0.12) is larger than the over-water values (0.07) from Wallops Island [3] and smaller than the desert data (0.35 for the daylight flights) obtained at Las Vegas [2]. Thus this value for moderate convection in rolling Midwestern terrain falls between the two extremes as might be expected.

Finally, the training of most present day meteorologists leads them to examine the geometry of their experiments to see if evidence of patterns or order emerge. Figures 15, 16, and 17 perform this function for Flights 3 and 4. These data show the unsmoothed tetroon positions in the vertical and transverse plane as one would see them looking downwind. The helical character of the patterns is immediately evident and we see that for the first 50 min. there are two opposing helical circulations. Slight smoothing of the data to reduce the small-scale variability would emphasize this even further. Previous tetroon flights have also shown helical circulations but the two-tetroon flights are the first that could show evidence of opposing circulations of this type and on this scale.

TABLE 3.—*Three-dimensional wind statistics*

Flight	$\overline{u}$ (kt.)	$\overline{v}$ (kt.)	$\overline{w}$ (kt.)	σ_u (kt.)	σ_v (kt.)	σ_w (kt.)	$\sigma_u/\overline{u}$	$\sigma_v/\overline{u}$	$\sigma_w/\overline{u}$
3	9.2	0.48	0.028	1.84	1.26	1.45	0.199	0.137	0.158
4	9.8	0.438	0.036	1.98	1.67	0.95	0.201	0.170	0.097

Comparison of the dimensions of these circulations with the dimensions inferred by Woodcock [15] from gull soaring shows very good agreement. Woodcock's figure 4 gives the total lateral extent of two opposing helices as 1000 m. and the vertical extent as 500 m. The tetroon flights show a lateral distance of 1600 m. and a vertical dimension very close to 500 m. Gifford [16] measured circulations very similar to these at Oak Ridge using "neutral" balloons and theodolites.

Beyond 50 min. the picture is less perfect but at this time the two tetroons were following very closely the same trajectory until about 85 min. after release. Even for this period and particularly after this time there is still evidence of helices and near the end of the flights the circulations are again in opposition.

The causative factors for these circulations are not known. Cincinnati pilot balloon data at 1700 GMT indicated that over the first 600 m. the wind shear vector was oriented toward 90° at about 2 m. sec.$^{-1}$, while from 600 to 1200 m. the shear vector was oriented north to south at 9 m. sec.$^{-1}$ Thus one has the choice of having the helices *parallel* to the shear in the layer in which the helices occurred, or *perpendicular* to the shear in the layer just above the helical circulations. In the absence of good radiosonde data (perhaps there was a slight capping inversion, or more stable layer, above 600 m. ?) these experiments can provide no definite answers to the relation between the circulations, atmospheric stability, and wind shear. In spite of the paucity of data it is informative to examine these circulations in the light of Townsend's [17] analyses of "Motion of Large Eddies", particularly his comments on the relation between the inclination of the circulation plane of the eddies to the mean wind and the growth and dissipation of these circulations. This angle is easily calculated from figures 15 and 16 for both flights. The tangent of this angle is simply the ratio of the total vertical extent of the eddy divided by the horizontal distance traveled during one complete circuit of the helix.

These distances were determined for Flights 3 and 4. This gives inclination angles between the plane of the circulation and the mean wind of 4° or 5° during the well-developed eddy. These are small, as required by Townsend's analysis.

Later in the flights, between 53 and 84 min., these angles increased to 12° for Flight 3 and 13° for Flight 4 while the circulations were deteriorating. This behavior is in the correct sense (i.e., increasing inclination) although Townsend predicts eddy destruction only after the plane of circulation is perpendicular to the mean flow. The area of the circulation should also decrease as the angle increases

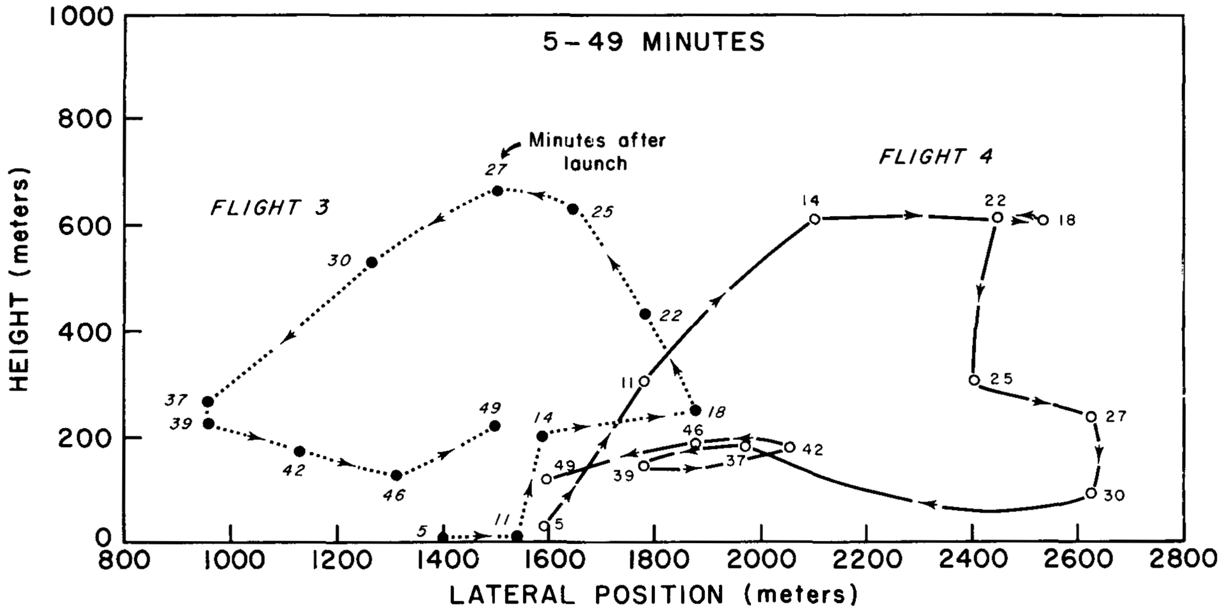

FIGURE 15.—Tetroon positions in the y–z plane 5–49 min. Numbers at position points are time after release.

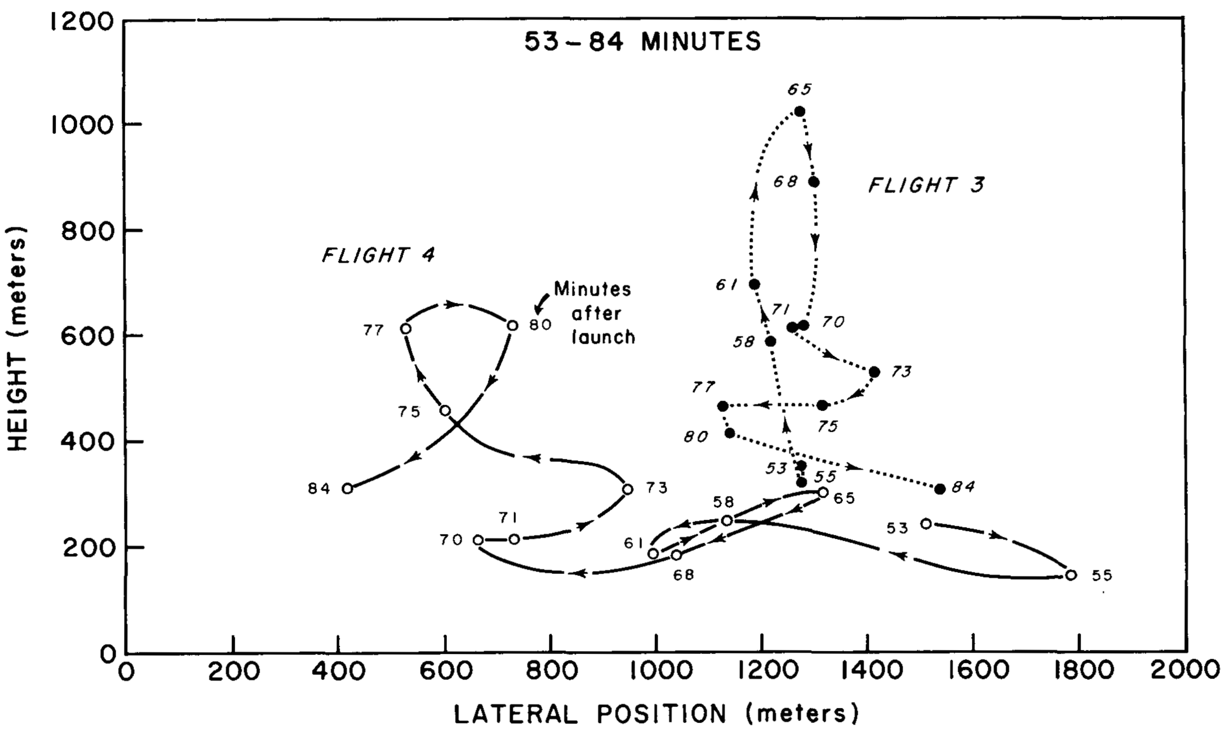

FIGURE 16.—Tetroon positions in the y–z plane 53–84 min.

and a glance at figures 15 and 16 also confirms this behavior.

Additional measurements of this kind would provide data to permit further quantitative evaluation of this approach and would offer a tool for determining the changing rate of energy removal from the mean flow.

5. CONCLUSIONS

These experiments have convincingly demonstrated:

a. Weather radar-tetroons-transponders can be used to obtain air trajectories near the ground and over distances of 10 to 20 mi. or more.

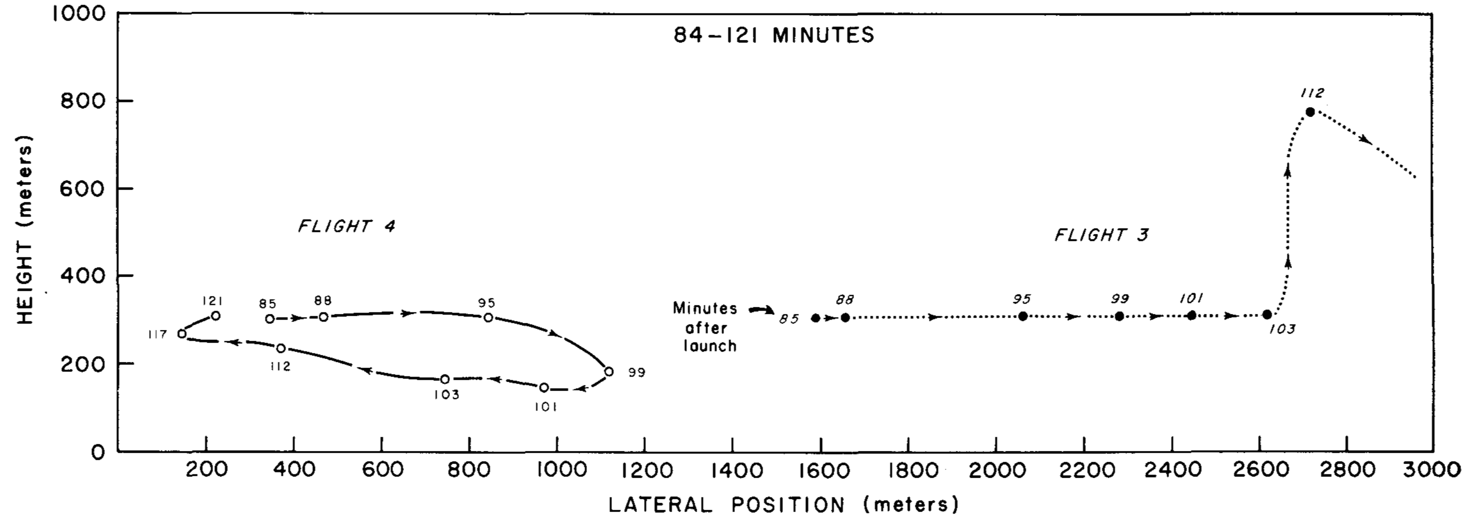

Figure 17.—Tetroon positions in the y–z plane 84–121 min.

b. Alternate positioning permits the simultaneous launch and tracking of two tetroons with a single radar and thus renders the classic "two-particle" dispersion experiment feasible over ranges of tens of miles.

c. The single two-tetroon release showed definite periodicities in the rate of "particle" separation, with negative separation rates (balloons moved closer together) over several extended intervals.

d. Vertical motion periods commensurate with the lapse rate were again observed and these appear to be independent of turbulence intensity.

e. Positive tetroon separation rates (with the cautionary note that this is a single experiment, not the required "ensemble") showed rates proportional to time which changed from a proportionality according to t^2 during the early stages to t^3 or even t^4 over later sections of the experiment. However, the average separation rate over the entire two-tetroon flight was proportional to t^2 or slightly less.

f. Eddy energy dissipation rates directly available from these data are in good agreement with determinations by other very different techniques.

g. The early, best ordered, portion of the paired flights (0 to 50 min.) showed adjacent helical circulations in the opposite sense extending over a downwind distance of about 8 n. mi. The dimensions of these circulations are nearly identical to those observed over the open ocean.

Thus these limited experiments which successfully achieved the designed objective have, in addition, added to our limited knowledge of low-level atmospheric behavior. They also indicate very clearly the complexity of this behavior and the promise of this technique in studying these complexities.

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REFERENCES

1. J. K. Angell and D. H. Pack, "Analysis of Some Preliminary Low-Level Constant Level Ballon (Tetroon) Flights," *Monthly Weather Review*, vol. 88, No. 7, July 1960, pp. 235–248.
2. J. K. Angell and D. H. Pack, "Estimation of Vertical Air Motions in Desert Terrain from Tetroon Flights," *Monthly Weather Review*, vol. 89, No. 8, Aug. 1961, pp. 273–283.

3. J. K. Angell and D. H. Pack, "Analysis of Low-Level Constant Volume Ballon (Tetroon) Flights from Wallops Is and," *Journal of the Atmospheric Sciences*, vol. 19, No. 1, Jan. 1962, pp. 87–98.
4. Vaughn D. Rockney, "The WSR–57 Radar," *Proceedings of the 7th Weather Radar Conference,* Miami Beach, Fla., Nov. 1958, Sec. F, pp. 14–20.
5. C. R. Dickson and E. F. Pound, "A Radar Transponder for Determining Meteorological Trajectories," *Proceedings of the 9th Weather Radar Conference,* Kansas City, Mo., Oct. 1961, pp. 379–383.
6. G. W. Brier, "The Statistical Theory of Turbulence and the Problem of Diffusion in the Atmosphere," *Journal of Meteorology,* vol. 7, No. 4, Apr. 1950, pp. 283–290.
7. G. K. Batchelor, "The Application of the Similarity Theory of Turbulence to Atmospheric Diffusion," *Quarterly Journal of the Royal Metecrological Society,* vol. 76, 1950, pp. 133–146.
8. F. G. Gifford, "Relative Atmospheric Diffusion of Smoke Puffs," *Journal of Meteorology,* vol. 14, No. 5, Oct. 1957, pp. 410–414.
9. F. G. Gifford, "Atmospheric Dispersion," *Nuclear Safety,* vol. 1, No. 3, 1961, p. 69.
10. J. K. Angell, "On the Use of Tetroons for the Estimation of Atmospheric Dispersion on the Mesoscale," *Monthly Weather Review,* vol. 90, No. 7, July 1962, pp. 263–270.
11. O. G. Sutton, *Micro-Meteorology,* McGraw-Hill Book Co., Inc., New York, 1953.
12. R. J. List (ed.), *Smithsonian Meteorological Tables,* Sixth Ed., 1951, p. 267.
13. H. H. Lettau, "Dissipation of Energy by Turbulence," *Journal of Meteorology,* vol. 18, No. 1, Jan. 1961, pp. 125–126.
14. E. K. Ball, "Viscous Dissipation in the Atmosphere," *Journal of Meteorology,* vol. 18, No. 4 Apr. 1961, pp. 553–557.
15. A. H. Woodcock, "Soaring Over the Open Sea," *Scientific Monthly,* vol. LV, Sept. 1942, pp. 226–232.
16. F. G. Gifford, "A Study of Low Level Air Trajectories at Oak Ridge, Tenn.," *Monthly Weather Review,* vol. 81, No. 7, July 1953, pp. 179–192.
17. A. A. Townsend, *The Structure of Turbulent Shear Flow,* University Press, Cambridge, 1956, 315 pp.